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INVESTIGATION OF CREEP PHENOMENA IN
POLYETHYLENE AND POLYPROPYLENE

JOHN W. EDGEMOND

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INVESTIGATION OF CREEP PHENOMENA IN

POLYETHYLENE AND POLYPROPYLENE

by

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Lieutenant, United States Navy
B.S., San Jose State College, 1957

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ABSTRACT

Although creep in thermoplastics has been investigated thoroughly, especially polyethylene, not too much information exists to establish activation energies at different stress levels by the application of high stress level, short time creep tests. Extrapolation of data to zero stress levels gives a true material activation energy which is a measure of internal resistance to deformation. Description of specific creep parameters and equipment with a relatively simple phototube recording device are offered along with a discussion of results and recommendations for future fields of investigation.

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Date	Description	Amount
1890-1-1	To Balance	100.00
1890-1-15	By Cash	50.00
1890-1-20	To Cash	25.00
1890-1-25	By Cash	75.00
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1. Introduction

Creep is generally defined as the time dependent deformation of material under constant load or stress. Although there has been much investigation of phenomenon of creep in metals, comparatively little information is available in the field of thermoplastics even though much theoretical work has been accomplished.

It is believed that creep is a result of a thermally activated process that is taking place in the material under consideration. In metals, for example, three possible mechanisms combine during creep deformation to account for creep behavior [1]. These are:

- 1) True internal frictional forces
- 2) Thermally activated processes
- 3) Quantum mechanical "tunneling" effects

True frictional forces give rise to a viscous or quasi-viscous behavior such as a rigid body moving in a viscous fluid.

Thermally activated processes are due in part to insufficient forces to provide movement. Some internal obstacles can be overcome if local thermal fluctuations supply the necessary energy. The rate that internal obstacles are overcome has been shown to depend on temperature in the form of $\exp(-\Delta H/kT)$ where ΔH is the activation energy of that specific process.

Quantum mechanical tunneling effects are incorporated in the applied force or stress and are considered independent (or indirectly dependent) on temperature.

Since the creep process is thought to be temperature dependent the creep rate can generally be expressed as

$$\dot{\epsilon} = \sum f_i(\sigma, T, st) e^{-\Delta H(\sigma, T, st)/kT} \quad (1)$$

where

$\dot{\epsilon}$ - creep rate (sec⁻¹)

f_i - frequency factor or the flux of diffusing atoms or vacancies

ΔH - activation energy which is dependent on stress (psi), temperature (°K) and a geometrical factor of the material

k - Boltzmann's constant (calories/mole °K)

Notice that time is not explicitly defined although it is incorporated in the $\dot{\epsilon}$ term which takes into account the structural change during deformation.

Eyring [2] has developed a somewhat similar formula for rate diffusion ν where a flow unit is considered to be a molecule.

$$\nu = \frac{kT}{h} e^{-\Delta f/kT} \quad (2)$$

where

ν - number of jumps per unit time

k - Boltzmann's constant (calories/mole °K)

h - Planck's constant (calories-second)

T - Temperature °K

Δf - Free energy for activation (calories/mole)

Sherby [3] develops the above equation further by considering the work done by stress is equal to the force times the distance the flow unit has to move for activation and shows that:

$$\dot{\epsilon} = \frac{2AkT}{h} e^{-\Delta f/kT} \sinh \frac{\tau A \lambda}{2kT} \quad (3)$$

where

A - shear strain rate (sec^{-1})

τ - shear stress (psi)

λ - distance of separation of molecules (in metals this would refer to lattice dimensions)

The distance the flow unit would have to move, therefore would be $\lambda/2$.

Experimentation has shown the $2AkT/h$ term has very little influence on the creep rate in comparison to the temperature effect, and the hyperbolic sine term can be considered to be a constant to the first approximation.

Since $\Delta F = \Delta H' - T\Delta S = N\Delta f$ and $k = R/N$ the equation now becomes

$$\dot{\epsilon} = A e^{-\Delta H'/RT} \sinh \frac{\tau \lambda}{2kT} \quad (4)$$

where

ΔF - free energy (calories)

$\Delta H'$ - energy of activation (calories/mole)

N - avogadeos number

R - gas constant

τ - shear stress (psi)

Letting a constant $B = A\lambda N/2$, τ = linear function of σ

and approximating $\sinh B\sigma/RT$ by $\frac{e^{B\sigma/RT}}{2}$ leads to

the following equation:

$$\dot{\epsilon} = \frac{A}{2} e^{-\Delta H'/RT} e^{\sigma B/RT} \quad (5)$$

A more general equation can now be stated because of the two constant terms $A/2$ and $e^{\sigma B/RT}$.

$$\dot{\epsilon} = K e^{-\Delta H'/RT} \quad (6)$$

Further study has shown that the constant K will depend on the parameters involved. Investigation of the effects of stress on the creep rate at constant structure at intermediate or high stress levels have shown that K varies as follows: [4]

high stress $K = S e^{\sigma B/RT}$

intermediate stress $K = S' \sigma^n$ where $n \sim 4$

where it has been found that the parameters B and n are independent of temperature and S and S' are the stress levels involved.

Theoretical interpretation of the above equations, plus experimental observation show there is an idealized creep curve and that the material reacts ideally for strain versus time according to Figure 1.

Since the area of investigation of this thesis is in the realm of high polymers, how does the foregoing fit into the creep phenomena observed in high polymers?

Creep study of non-metallic material probably dates back to 1905 when Phillips published the results of his observations [5]. His work included creep observations of rubber and glass.

In the late 1930's and early 1940's, much theoretical work was being carried out to establish mathematical models to describe creep experiments. Among the models proposed was the Voigt-Kelvin formulation which was based on a series of spring constants in parallel

with dash pots. A similar model called the Maxwell Wiechert Model consisted of parallel branches made up of one spring constant and a dash pot each [6] .

In a review of concepts and definitions Turner [7] lists as a basic total strain equation:

$$\epsilon_t = \epsilon_0 + \psi(t) + \sigma t / \eta_0 \quad (7)$$

where

ϵ_0 - instantaneous strain

$\psi(t)$ - is called the creep function

η_0 - viscosity coefficient

t - time

σ - stress

The instantaneous strain component ϵ_0 is associated with bond angle distortion and bond stretching, $\psi(t)$ is associated with the rotation of molecular segments or groups of segments while the third term is associated with the large scale relative movements of the whole molecule with respect to its neighbors.

All these terms appear to be associated with internal energies which to a great extent are temperature and stress dependent. In the examination of this equation one cannot help but to go back and compare term by term the basis of development of the rate equation for creep. Bond angle energy distortion can be compared to the Peierles force which holds a dislocation in its low energy position in a lattice. The creep function $\psi(t)$ can be associated with

dislocation tangles, and the large scale relative movement of molecules can be associated with ζ (rate diffusion of a flow unit) which in turn can be associated with Fick's laws of diffusion.

This then leads us back to a form of equation (6) that was developed earlier.

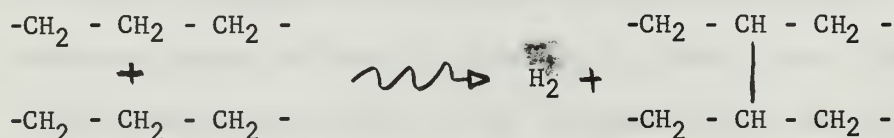
Since the creep rate is a process of dislocation climbs in metals, it would not be surprising to find that, since polymers are long chained molecules, the movement of these chains past one another is also rate controlled. It is therefore, one of the goals of this paper to examine the activation energy $\Delta H'$ for the two polymers to find any correlation with stress or temperature.

2. POLYMER IRRADIATION

Chapiro [8] has very deeply reviewed the field of irradiated polymers. It has been shown that many polymers undergo a degradation process which causes internal cross linking between polymer chains.

The first detailed study of polyethylene irradiation was published back in 1952 where it was found that the physical properties changes proportionally to the amount of radiation received. It was found that certain physical properties improved to a certain point then tapered off as the radiation was increased.

The chemical process involved in cross-linking is assumed to be as follows:



where H_2 is liberated in the process.

Where Polyethylene is heavily irradiated it becomes very hard and brittle and takes on the appearance of a dark tinted transparent glass.

Some of the physical changes brought about by irradiation are:

- a. increase in melting temperature
- b. increase in density and decrease in specific volume due to the cross linking pulling the polymer chains closer together
- c. gradual destruction of the crystalite regions

Polypropylene has not been studied to the extent that polyethylene has and not much information is available. However, preliminary investigations have shown that polypropylene acts very similarly to polyethylene with respect to change in physical properties and undergoes a similar degradation which forms cross links between chains.

Even though much work has been reported on the subject of irradiation of plastics, only a few reports on the effects of creep have been found. Irradiated samples were subjected to the creep procedure to show the differences, compared to unirradiated samples.

3. EXPERIMENTAL DETAIL

Examination of creep data for metals shows that metals exhibit curves very similar to that of Figure 1. There is no real structure change, that is to say, crystal change, and that resistance to deformation is caused by dislocations, tangles, inclusions, and vacancy diffusion if the temperature is low enough to discourage recrystallization.

The two plastics under investigation, however, do undergo a change from an "amorphous" or random material to that of an orientated material which can almost be called crystalline.

Figure 2 shows a tensile test of polyethylene and polypropylene where, after an initial maximum load, the test bar settled down to a constant load value while the material still was deforming. Kinney [9] has stated that the material is undergoing orientation which is aligning up all the random oriented chains into a material that is more crystalline. The original specimens stretched 900% during the tensile test before failure. Figure 2 also shows a "before and after" sample of the plastics. It is also noted here that during the test a substantial cross sectional area reduction of approximately 75% was observed.

Further proof that the plastics are under going a structure change can be seen in Figure 3, which shows an Xray diffraction patters for both plastics, in the natural state and in the deformed state.

From Xray diffraction study and the Bragg equation [10]

where
$$n\lambda = 2d \sin \theta \quad (8)$$

n = order or number of the reflection

λ = wave length of incident ray

d = distance between the reflecting adjacent planes

θ = angle of reflection

It is not hard to correlate the pictures in Figure 3 to similar Xray pictures of metals in the random or polycrystalline and orientated

states. Since the carbon atoms are poor Xray scatterers, further study in this direction could best be undertaken with neutron beam scattering techniques.

A point to make here is that these two plastics might display not just the three creep stages as in the ideal curve but four states of creep, the second and third stages being those for the amorphous material and the orientated material, in that order. The creep studies for which this report is intended will be limited to the creep phenomena which is thought to be in the amorphous or random state material.

There are many accepted methods for the determination of the activation energy ΔH . One method is the interrupted quench method where a material is subjected to a constant load at a constant temperature until a creep rate is established. Then it is immediately quenched to another temperature which is held constant. A second strain rate is established. With the help of equation (6) the two different conditions are set up and equated to each other.

Since it is assumed the process is only thermally activated the constant K is the same for both conditions. ΔH is then computed.

A second method is that the tests are carried to failure which is called creep rupture. Here it is assumed that the constant K is a function of time. The two different conditions are then equated against each other, the only change is that K is replaced by the different rupture times. ΔH is then computed.

The intent of this study is to examine one of the proposed creep mechanisms which is not mentioned above. The object is to examine short time high stress level conditions to see if the two polymers will follow a relationship such as equation (6)

$$\dot{\epsilon} = K e^{-\Delta H'/RT}$$

where

$$K = S e^{B\sigma/RT}$$

The materials under consideration will be high density polyethylene and polypropylene.

4. EXPERIMENTAL APPARATUS

Several efficient methods have been designed to investigate the phenomena of creep. The method chosen here is based on a design that has long been in use in the metallurgy field. The basic unit is a fulcrum beam the weights placed on one end and on the other end a cable is attached to a fixed specimen. This then applies a constant load to the specimen. Figure 4 shows several pictures of the experimental apparatus.

The weighing unit is basically a fulcrum with a ratio of 2.98 to 1 with the end cables set on a radius from the point of balance to eliminate a change in lever arm as the specimen is deformed. The cable opposite the weighted end is attached to a shutter that passes in front of a phototube. This shutter controls a beam of light passing from a light source to the phototube. The lower end of the shutter is connected to a bar which extends into the oil pot. At the end of this bar is the specimen which is fixed at the lower end.

This phototube recorder is similar to that proposed by Scheer and Palmer [11] . The greatest asset this type of recording gear performs is that the experimenter does not have to live next to a cathetometer to take all the necessary readings. This recording instrument is fully automatic and produces a creep curve of specimen extension versus time.

Calibration of the phototube and readings taken by a cathetometer showed the phototube voltage output to be fairly linear (Figure 5). Figure 6 shows a schematic wiring diagram with the necessary power supplies required to activate this recorder. The 250 volt DC power supply is a Lambda Regulated Power Supply Model 71. The recorder is a standard 20 MV range Leeds and Northrup Speedomax Recorder, the light supply is a collimated 6 volt light bulb. The phototube is a RCA 919 tube.

Figure 7 shows a cutaway of the oil bath and the specimen mounting. Although the two plastics in question are chemically inert to most solvents, acids, and water, it was not known whether immersion in the silicone oil bath would change the creep characteristics of the material. In fact, much work has been done in silicone oil baths. In a review of brittle fracture of glass by Phillips [12] it has been shown that glass (and other materials) materially increased its tensile strength properties greatly by testing when completely immersed in water. Since time would not allow testing both in air and silicone oil to see if there was a material change in the properties, it was elected to test the specimens in air by lowering

the specimen down inside a copper tube sealed at one end which is immersed in the oil bath. A thermocouple attached to the specimen was used to check the temperature. A Leeds and Northrup 110 volt Controller was attached to the oil bath for constant temperature control.

The American Society for Testing and Materials has recommended certain standards of procedure for long time creep tests of plastics under compression or tension loads (ASTM designation D 674-56).

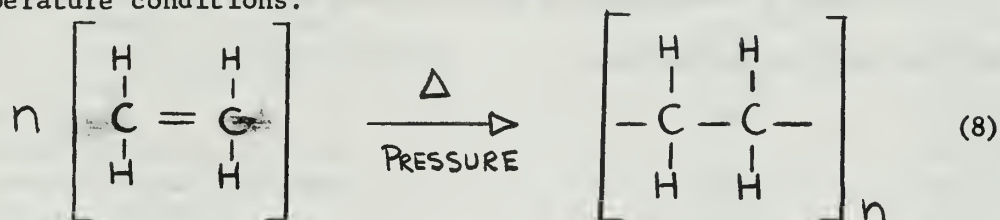
Even though the ASTM recommends certain requirements and procedures to be followed, these are by no means standardized as concisely as the procedures used for metals. In fact, ASTM still solicits data in any form for plastics as long as it is fully documented.

The ASTM standards were followed as far as temperature gradient of the specimen was concerned. For 36 hours the temperature gradient for a two and one half inch length specimen was between 0.2 to 0.3° Celsius.

The specimen used for this study was not according to the recommended ASTM standards. Since the phototube was limited to a one inch recording range and previous tests have shown that a constant strain rate was established in this range, the sample gage length was 1.625 inches.

5. MATERIALS, PROPERTIES AND CHEMISTRY

Polyethylene is a thermoplastic resin made from the polymerization of ethylene under carefully controlled pressure and temperature conditions.

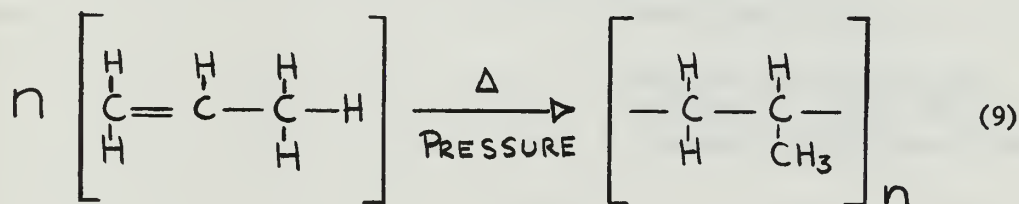


In its natural state polyethylene has a waxy-white translucent appearance. It can be made into thin films, sheets, rods and filaments and can be molded easily.

It can have a wide range of colors, and it is tough, hard and flexible. It also has unusually good moisture resistance, chemical inertness and excellent electrical properties.

Polypropylene started from an outgrowth of research of the polymerization of ethylene. It was found that higher alkenes could also be polymerized into useful polymers.

Polypropylene was produced in the United States in the late 1957's. The overall polymerization reaction is:



Some of its natural properties are that it is highly crystalline with a high softening temperature, high resistance to solvents, and

has none of the waxy feeling of polyethylene. In its molded form it has better scratch resistance, and is stiffer and harder than polyethylene.

Table I shows a comparison of the physical properties of both polyethylene and polypropylene.

TABLE I

PHYSICAL PROPERTIES

<u>Mechanical Properties</u>	<u>Polypropylene</u>	<u>Polyethylene</u>
Impact strength ft-lb/in.	.6-6.0	1.5-20
Ultimate tensile strength 1000 psi	5.0	2.5-5.0
Yield strength 1000 psi	4.97	2.5-5.0
Elongation %	220	15-100
Flexural strength 1000 psi	8	No fracture
Flexural modulus 1000 psi	170	100-260
Rockwell, hardness	D785	R30-R50
Deformation under load (122°F, 2000 psi)%	2.0	8.16
<u>Physical Properties</u>		
Specific gravity	.90-91	.941-.965
Melting point °F	330	250-260
Heat distortion point °F		
66 psi	221	140-180
264 psi	-	113
Coefficient of thermal expansion °F	6.2×10^{-5}	9×10^{-5}
Thermal conductivity btu/hr/sq ft/°F/in.	.95	2
Water absorption (24 hr.)%	.01	<.01
<u>Electrical Properties</u>		
Dielectric strength volts/mil	500-660	480
Dielectric constant		
10^3 cps	2.2-2.3	2.3
10^6 cps	2.2-2.3	2.3
Volume Resistance - OHM-CM	$>10^{16}$	$>10^{16}$

From: "Modern Plastics
Encyclopedia 1965"

"Source Book of the New
Plastics", Simons H. R.,
Reinhold Publishing Corp. 1959

6. EXPERIMENTAL RESULTS

When calculating an activation energy, it becomes necessary to define a few new terms. From an equation that was developed earlier

$$\dot{\epsilon} = K e^{-\Delta H'/RT} \quad \text{WHERE } K = S e^{B\sigma/RT} \quad (10)$$

the terms when rearranged will yield the following

$$\dot{\epsilon} = S e^{-\frac{\Delta H' + B\sigma}{RT}} \quad (11)$$

If one considers the term $(\Delta H' - B\sigma)$ to be a form of activation energy which is dependent on stress, then one can consider this to be a process activation energy ΔH , where

$$\Delta H = (\Delta H' - B\sigma) \quad (12)$$

Since the constant B is a material constant which is dependent only on the material, it can be seen that the process energy ΔH will equal the material energy $\Delta H'$, if the state of stress of the material is zero.

Another consideration is the structure factor S. It has been shown earlier that there is a structure change in both materials as deformation increases. This parameter can be eliminated by assuming that the structure change is proportional to the strain and suggests that for a given strain at constant stress the process activation

energy could be calculated by setting up two contrasting temperature conditions for which the stress and strain are constant:

$$\frac{\dot{\epsilon}_1}{\dot{\epsilon}_2} = \frac{S e^{-\Delta H'/RT_1}}{S e^{-\Delta H'/RT_2}} \quad (13)$$

rearranging

$$\ln \frac{\dot{\epsilon}_1}{\dot{\epsilon}_2} = -\frac{\Delta H'}{R} \left[\frac{1}{T_1} - \frac{1}{T_2} \right] \quad (14)$$

and solving for

$$\Delta H' = \left[\frac{T_2 T_1}{T_2 - T_1} \right] R \ln \frac{\dot{\epsilon}_1}{\dot{\epsilon}_2} \quad (15)$$

From the actual creep curves (Figures 8 and 9), the instantaneous creep rates $\dot{\epsilon}$, and true strain δ were calculated at various points along each curve. The instantaneous creep rate and true strain were plotted as shown in Figures 10 and 11, from which were calculated the process energies $\Delta H'$.

Considering a strain after the point at which the creep rates become constant will yield the energy $\Delta H'$ listed in Table II.

The values from Table II for stress vs $\Delta H'$ are plotted in Figure 12. Extrapolating the data to zero stress will yield the activation energy which can be classified as a true activation energy of the material.

High temperature viscosity measurements of high density polyethylene have given activation energies of 12 to 14 Kcal per mole

at temperatures in excess of 400°K [13, 14, 15]. The extrapolated value of ΔH for polyethylene as in Figure 12 agrees very favorably with accepted published values.

In trying to correlate the idea that irradiated materials should increase their true activation energy, specimens of polypropylene were subjected to various radiation levels and then subjected to the creep procedure. The results of this test were inconclusive as the creep trace showed very little difference from the unirradiated sample. Although there appeared to be a tendency to increase ΔH by showing that for an established set of conditions the creep rates were lower for the irradiated polypropylene, the differences were not enough to be determined within the accuracy of the experimental apparatus.

The levels of radiation used to irradiate the polypropylene were not suitable. The local source had a maximum level of 10^9 thermal neutrons per cm^2 which did not produce enough crosslinking to be detected by our apparatus. The other radiation levels used were greater than 10^{18} thermal neutrons per cm^2 which made the samples very weak and brittle.

TABLE 2

CALCULATED VALUES FOR ACTIVATION ENERGIES

 $\Delta H'$

Polypropylene Stress in psi	$\Delta H'$ in kcal per mole
900	24.8 True ΔH from Figure 12
1300	27.1 =21.5
1450	28.6
1800	29.0
2000	30.8
Polyethylene Stress in psi	$\Delta H'$ in kcal per mole
970	17.0 True ΔH from Figure 12
1100	17.7 =12.1
1300	19.0
1600	20.1

7. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this experiment was to calculate the activation energy of two different thermoplastic resins by use of a simply designed experimental set-up that would establish a constant creep rate for a high stress, short time creep test. This method gives a recorded trace of the whole history of a particular run, and is adequate for most of this work. For small changes, such as the minimal crosslinking of the samples irradiated at 10^9 thermal neutrons per cm^2 , a more sensitive instrument would be required.

The high levels of radiation greater than 10^{18} thermal neutrons per cm^2 were chosen because of data (from reference 8) for polyethylene, and it was assumed that this would be suitable for polypropylene. However, this level of radiation was too high and destroyed the utility of this material.

It is very evident that polyethylene is less subject to radiation damage than polypropylene for given radiation levels, which might be due in part to the extra methyl group of polypropylene crosslinking at the same time the chains are linking causing the degradation process to progress at a much faster rate.

It is the understanding of this writer that radiation damage effects have been studied by use of Electron Magnetic Resonance (EMR) and since polypropylene apparently is more susceptible to radiation damage, it might be due to the methyl radical which can be studied by this method.

It is suggested that radiation effects for polypropylene on creep properties and activation energies should be studied in the range of 10^9 to 10^{18} thermal neutrons per cm^2 as it is apparent from either extreme that the polypropylene material changes its physical properties greatly within this range.

There is little doubt that at radiation levels higher than 10^9 thermal neutrons per cm^2 , ΔH versus radiation relationship could have been established. Also it is reasonable to assume that, since the data to establish the material activation energies for polyethylene agrees with published values established by different methods, it is also reasonable that the values for polypropylene are equally as valid.

Although the design principle of the apparatus gives satisfactory results for plastics, it is not suitable for work with metals or other material with a high Modulus of Elasticity. The recording

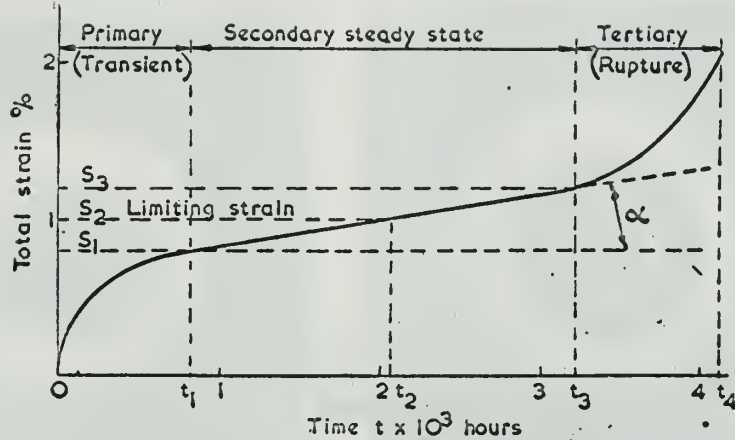
ranges along with the light controlling source will have to be modified to increase the ability to detect smaller changes in deformation. By comparing the recorded creep traces at the same stress and temperature conditions showed very good agreement over eight hour tests to show the data to be very reproducible.

I would like to acknowledge the help and assistance given me by Professor J. Sinclair, and Laboratory Technicians R. Edwards and W. Penpraze who kept me going in the right direction.

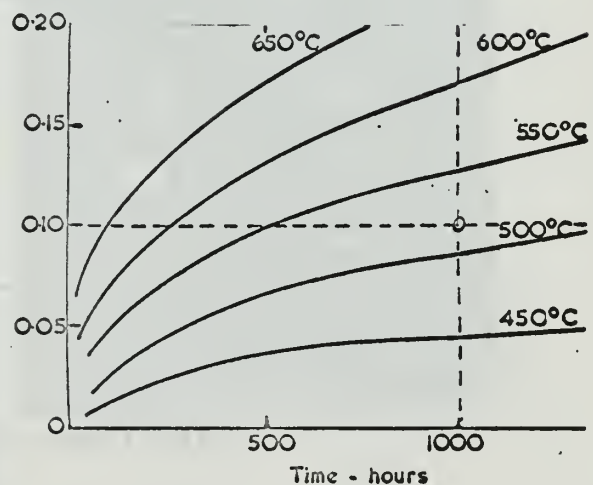
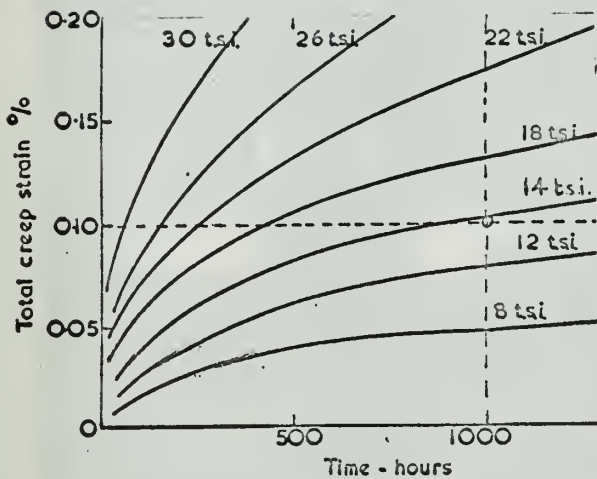
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FIGURE 1 IDEALIZED CREEP CURVES



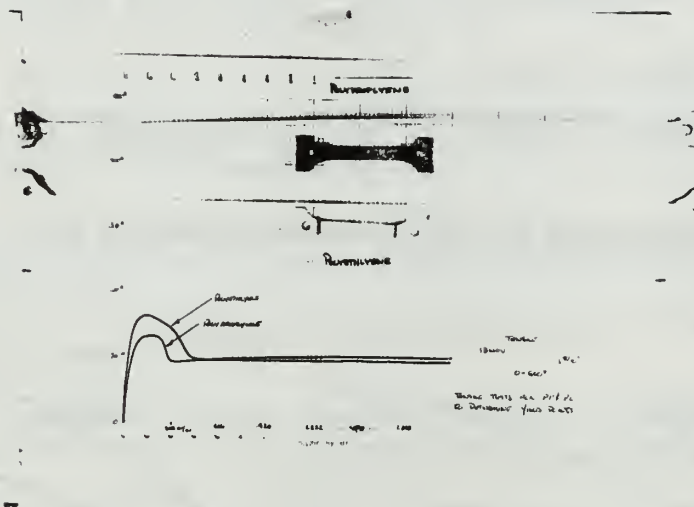
Typical curve of creep strain v. time. Limiting strain shown as at 1%; steady state gradient by α



Typical set of creep curves such as might be obtained with a low alloy steel, showing methods of presenting and deriving data. (a) Results with different stresses at one temp. (say 450°C). (b) Results with different temperatures at one stress (say 8 tsi)

FROM: TWEEDDALE, J.G., MECHANICAL PROPERTIES OF METALS,
AMERICAN ELSEVIER PUBLISHING CO.
1964

FIGURE 2



SPECIMEN DATA

POLYPROPYLENE--ULTIMATE STRENGTH--4860 psi
 CONSTANT "NECKING"
 STRENGTH-----3020 psi
 % ELONGATION-----800

POLYETHYLENE---ULTIMATE STRENGTH--3500 psi
 CONSTANT "NECKING"
 STRENGTH-----2180 psi
 % ELONGATION -----900

FIGURE 3

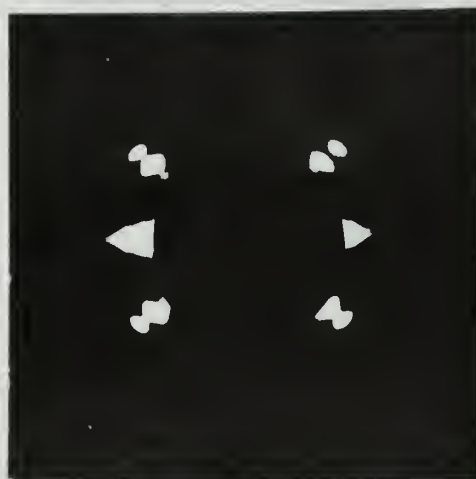
ARRAY DIFFRACTION PATTERNS

POLYETHYLENE

POLYPROPYLENE



NATURAL CONDITION



DEFORMED BY STRETCHING

PICTURE DATA
EXPOSURE TIME-1.5 HOURS
@ 50 KVA, 20 MA
TUNGSTEN FILAMENT ARRAY
TUBE

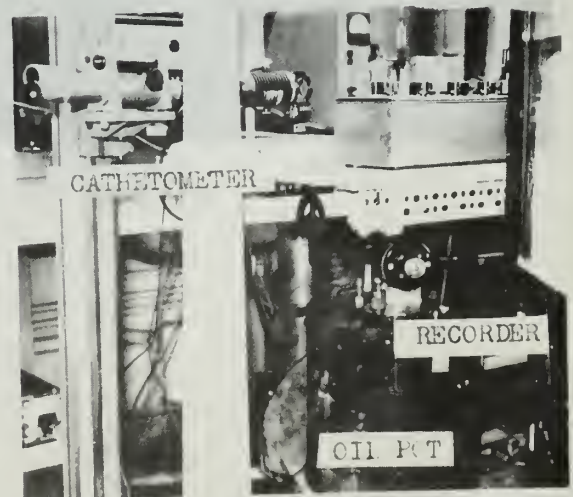
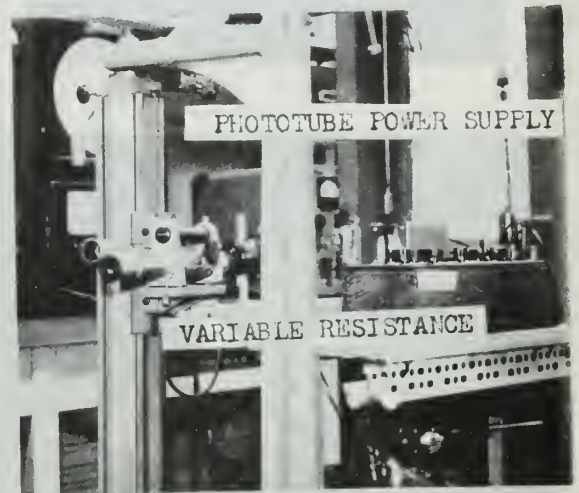
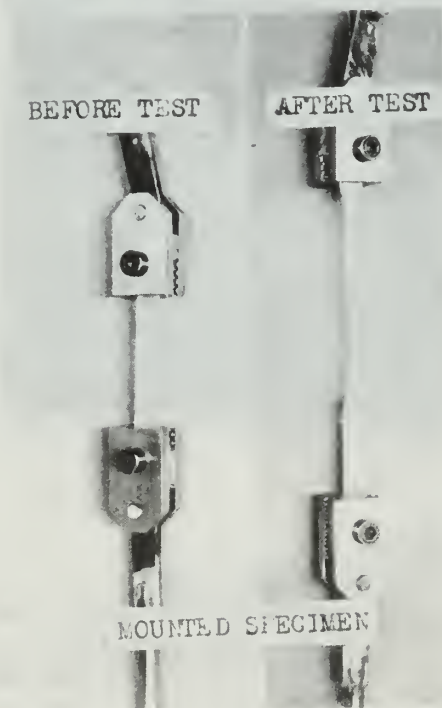
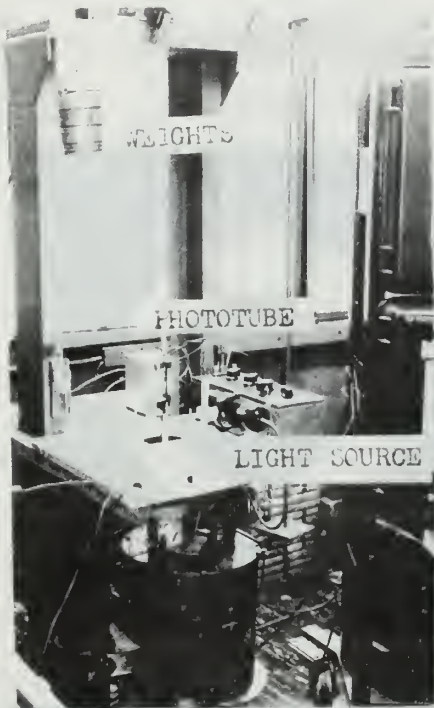


Figure 4
Various views of
the apparatus
used in the
test.

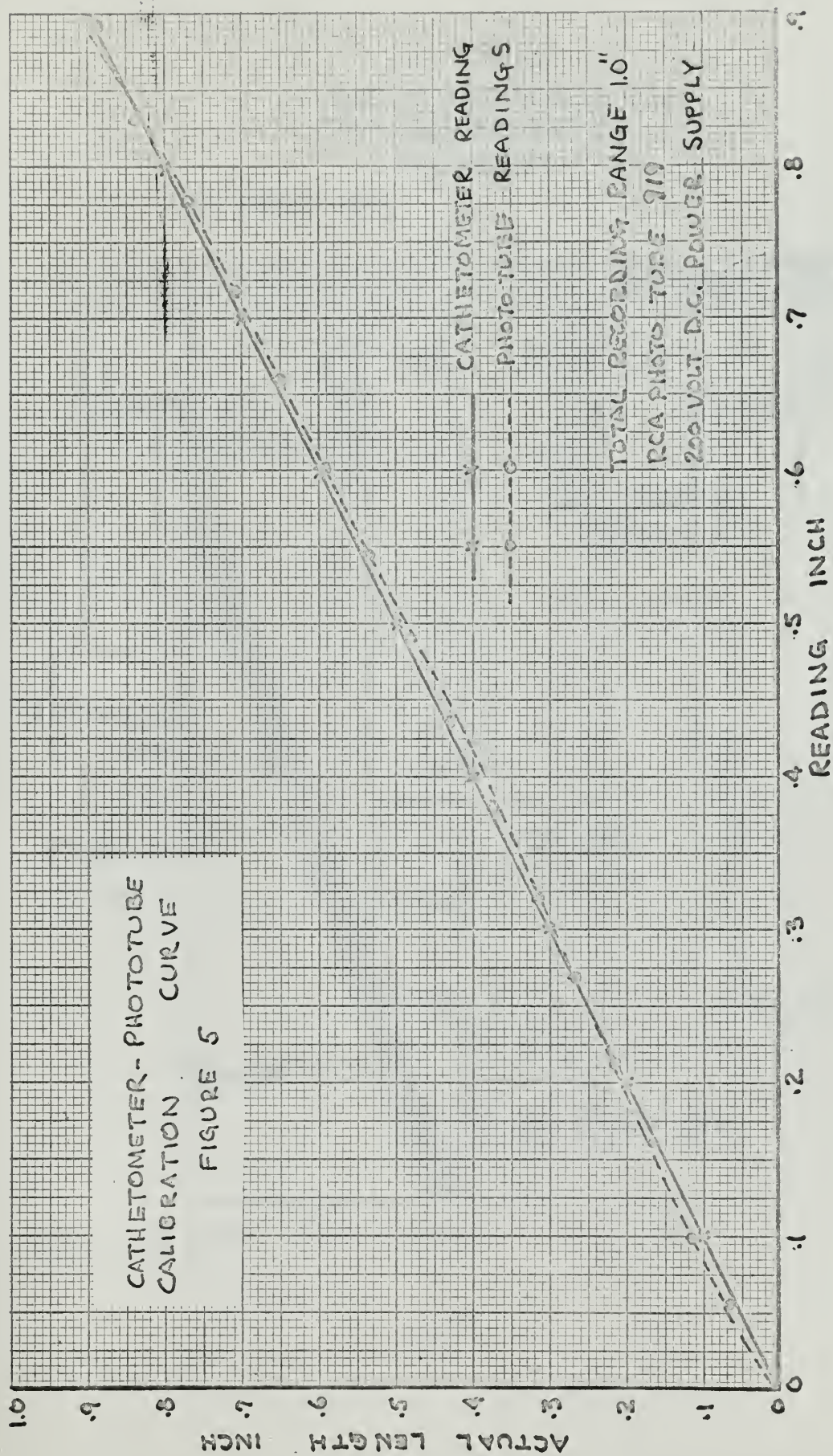
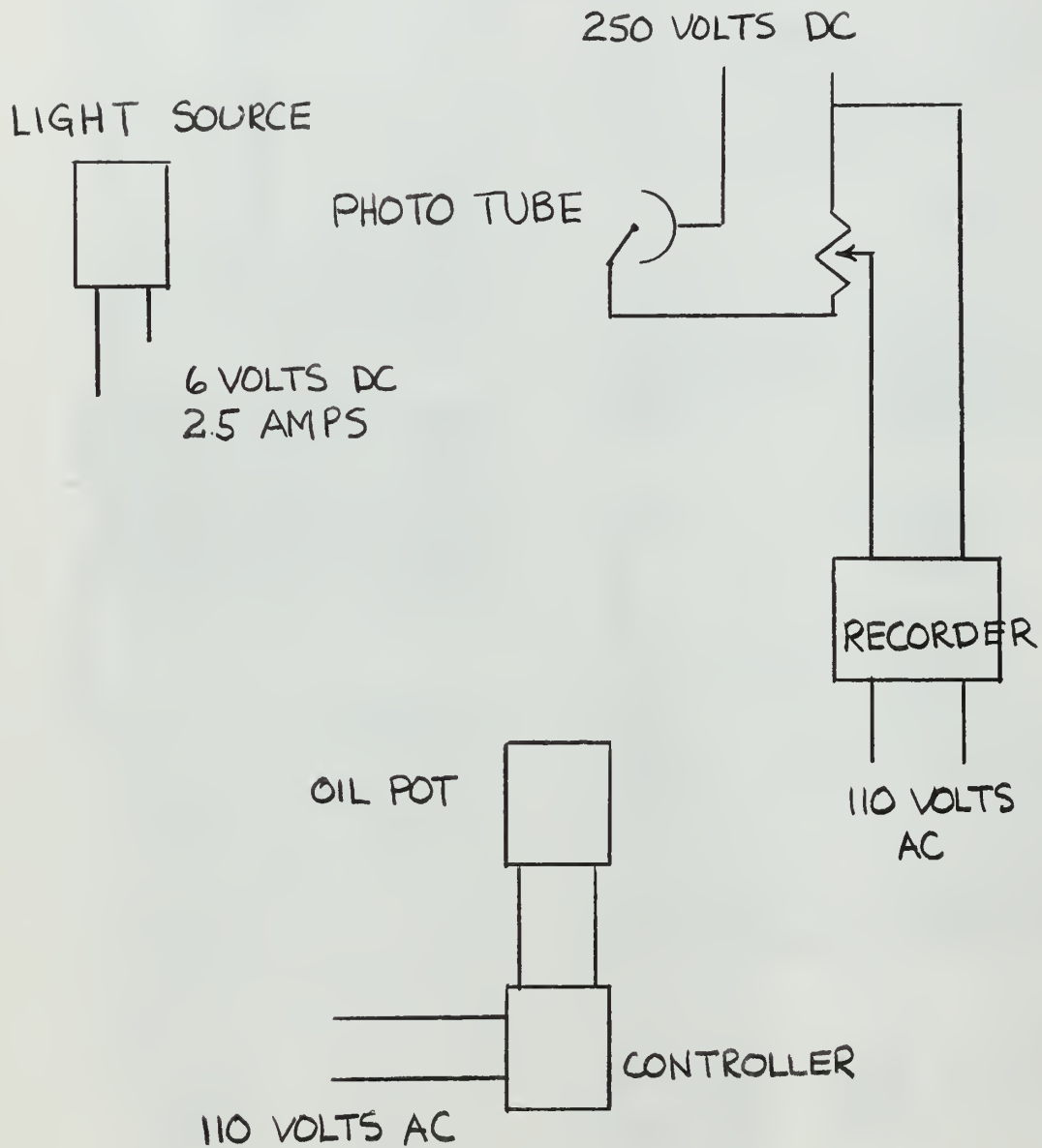
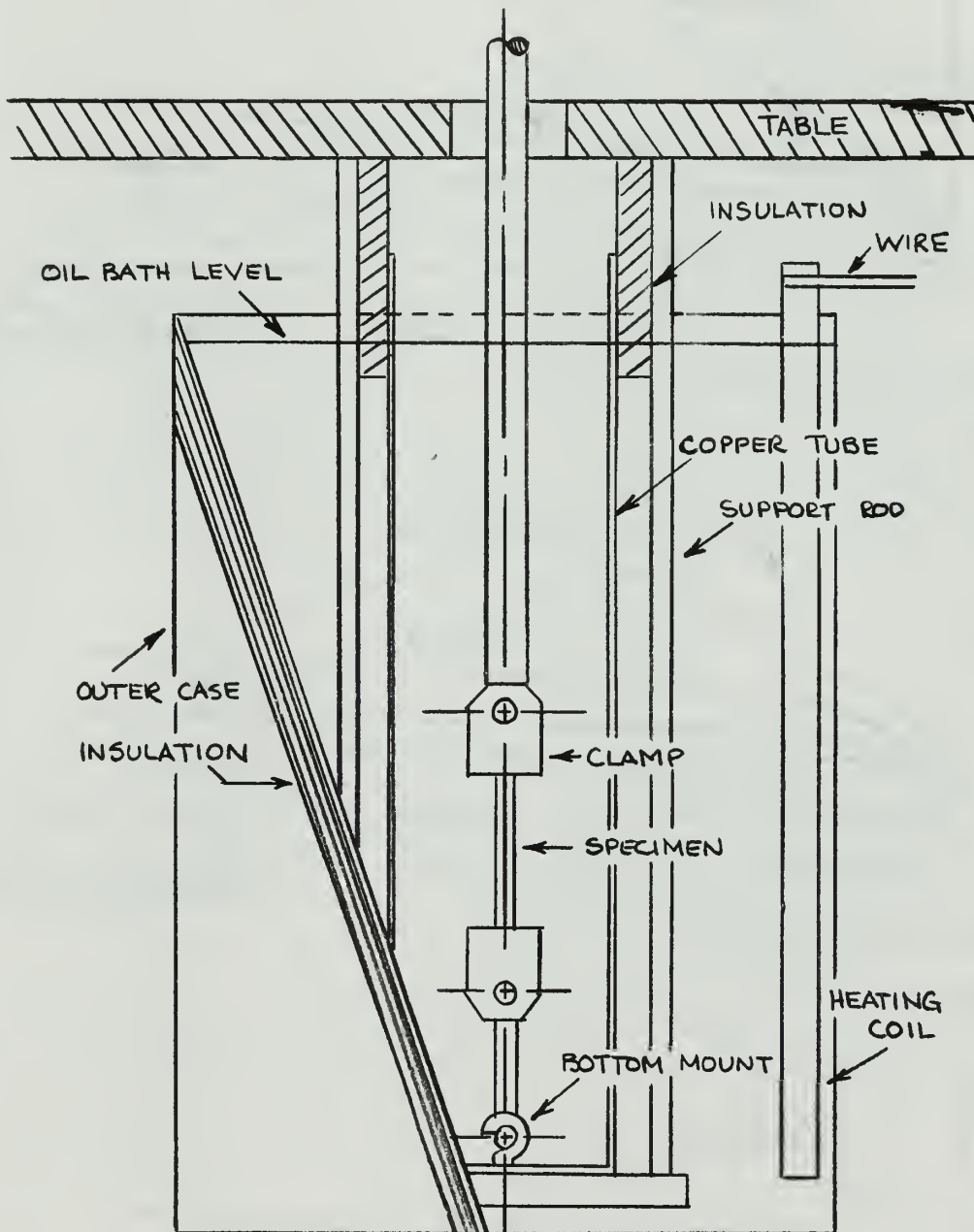


FIGURE 6

SCHEMATIC WIRE
DIAGRAM

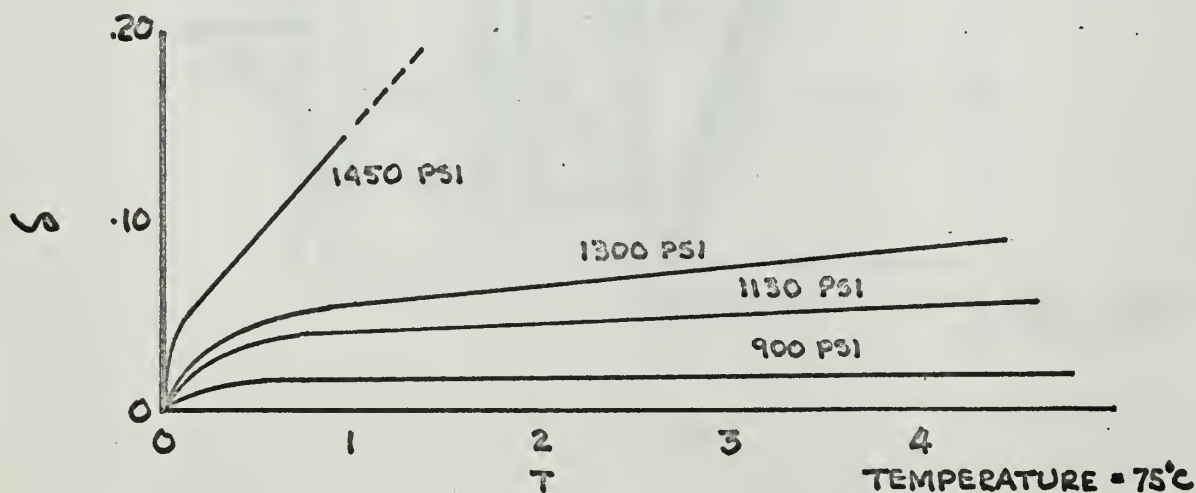
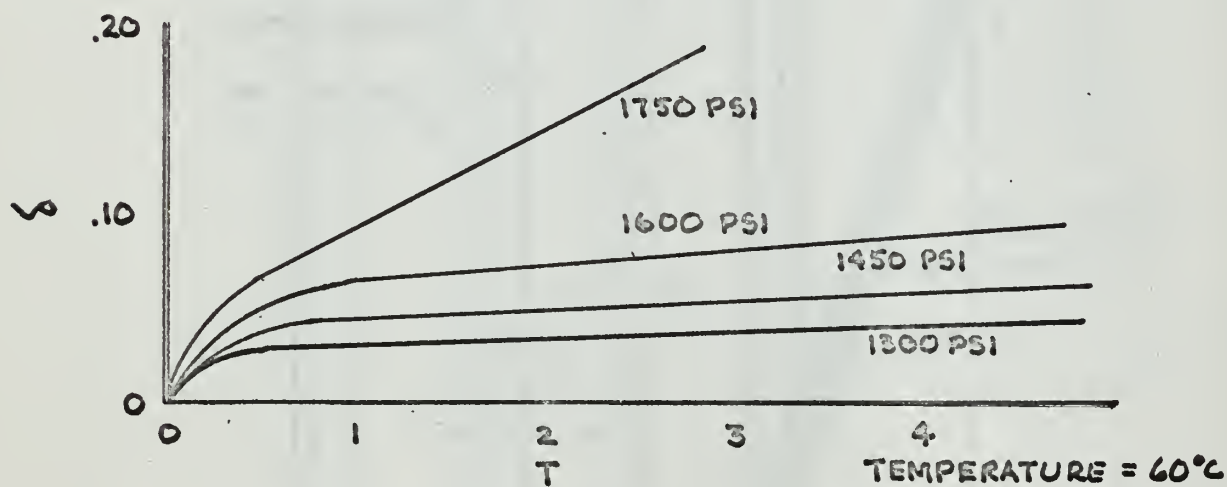
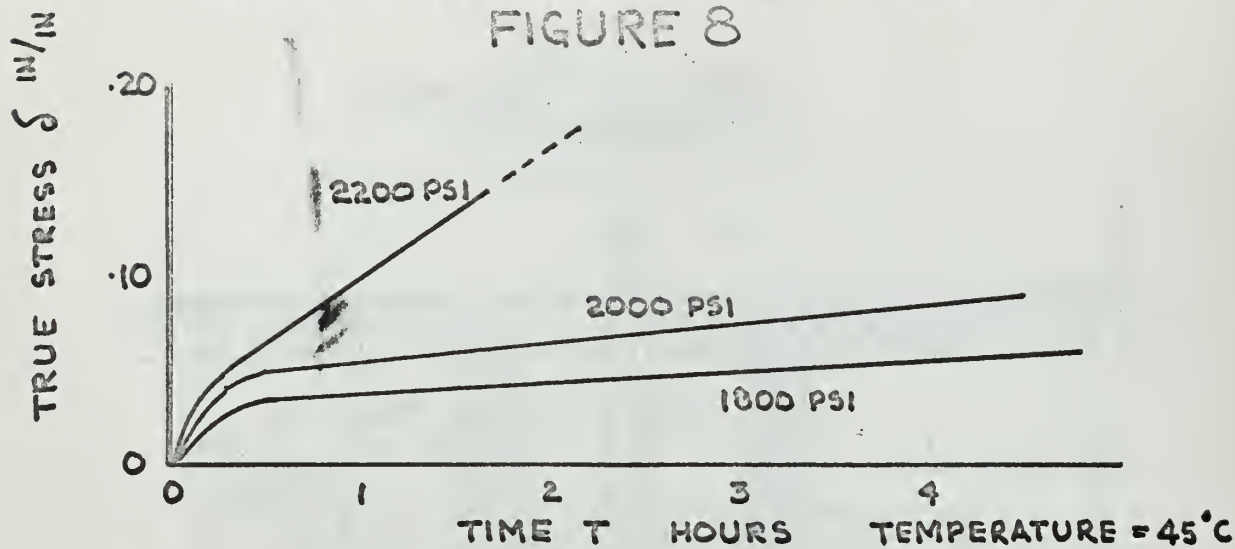


MOUNTED SPECIMEN
FIGURE 7

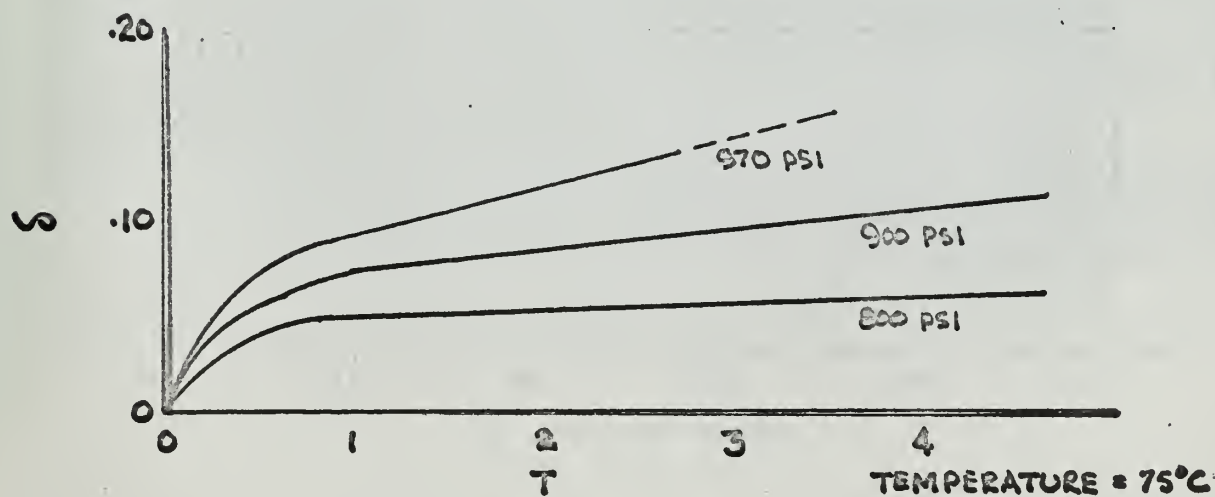
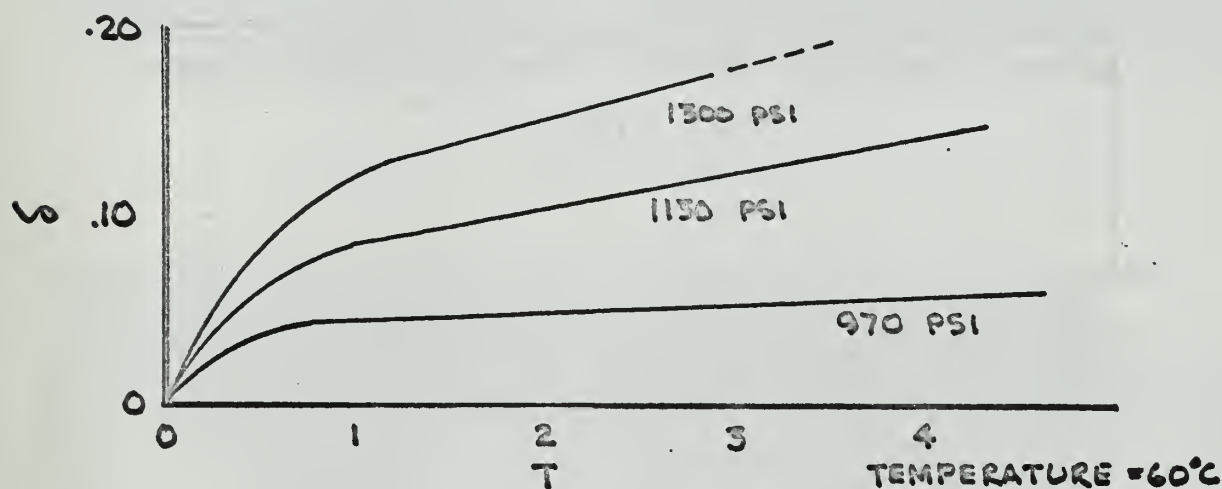
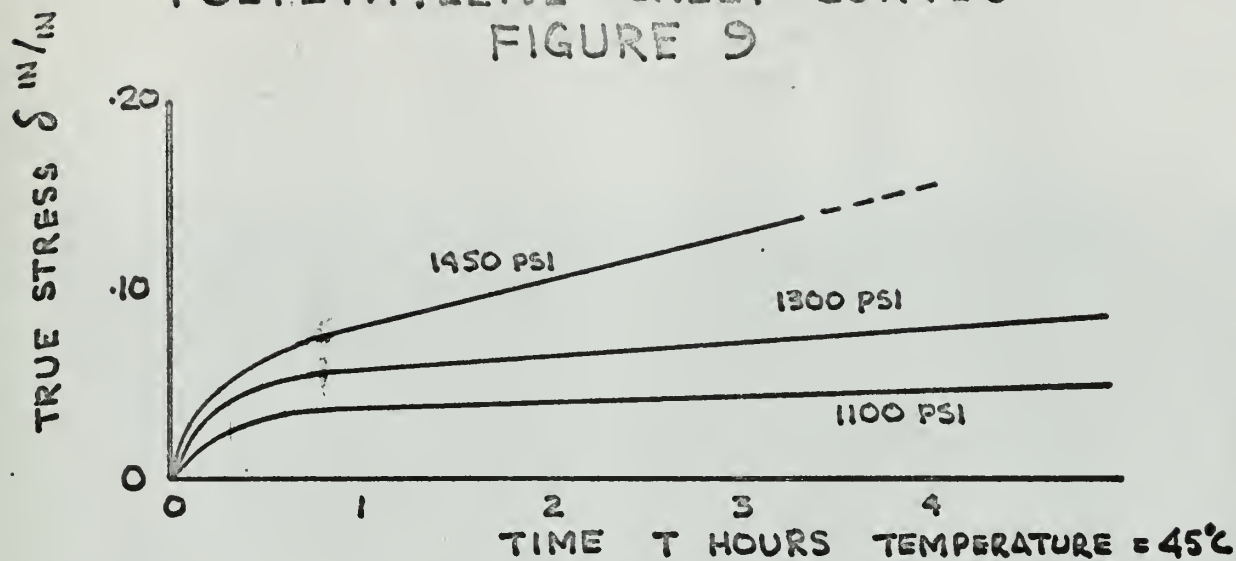


NOTE: NOT SHOWN IS CIRCULATING
MOTOR FOR OIL

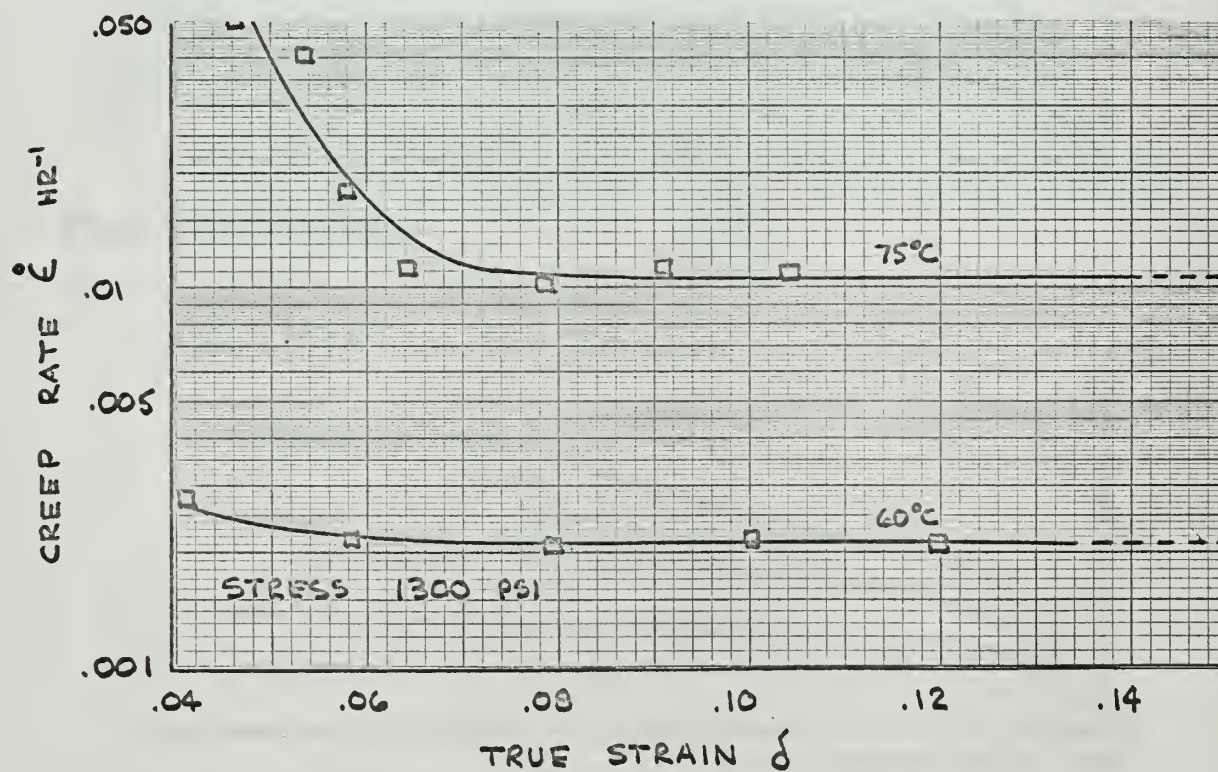
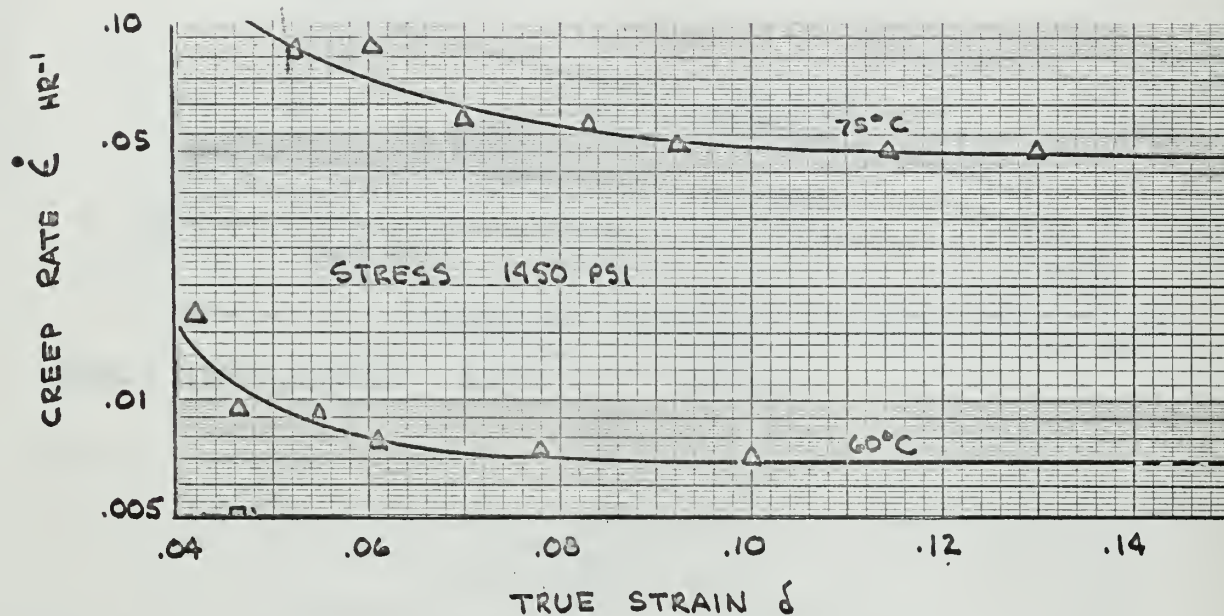
POLYPROPYLENE CREEP CURVES FIGURE 8



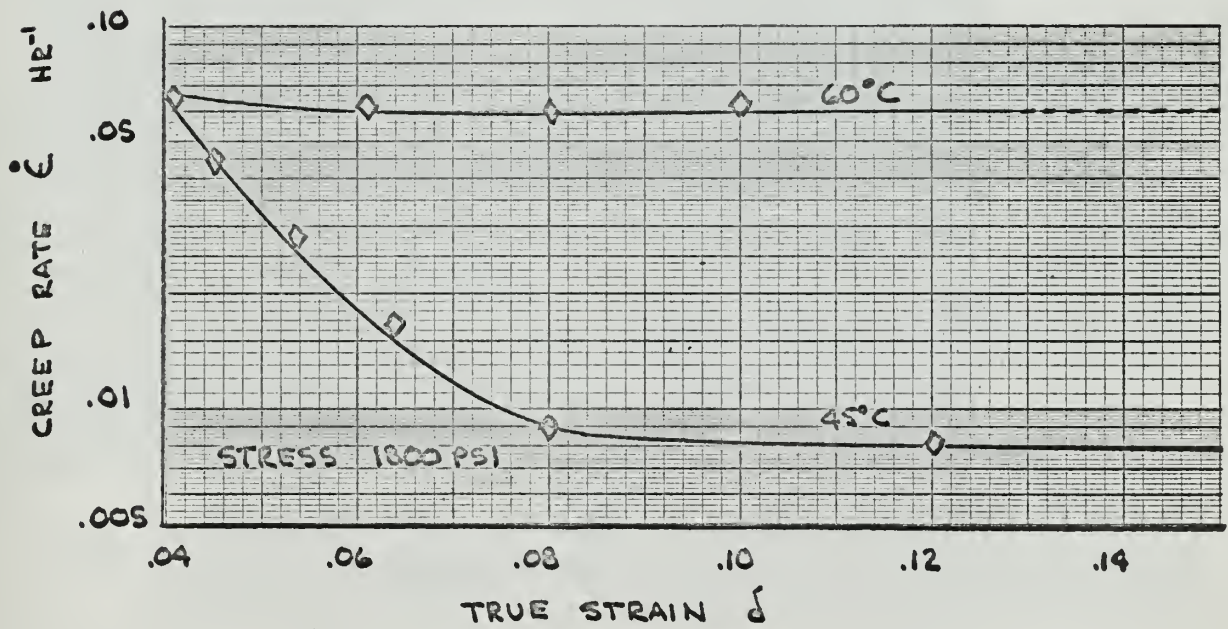
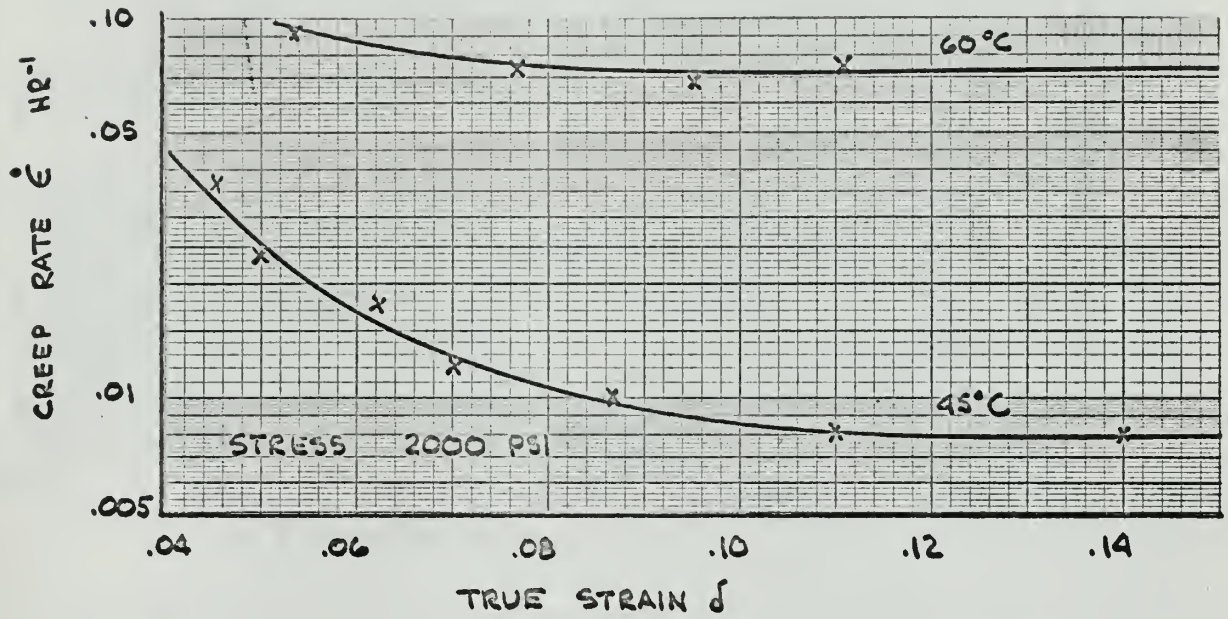
POLYETHYLENE CREEP CURVES FIGURE 9



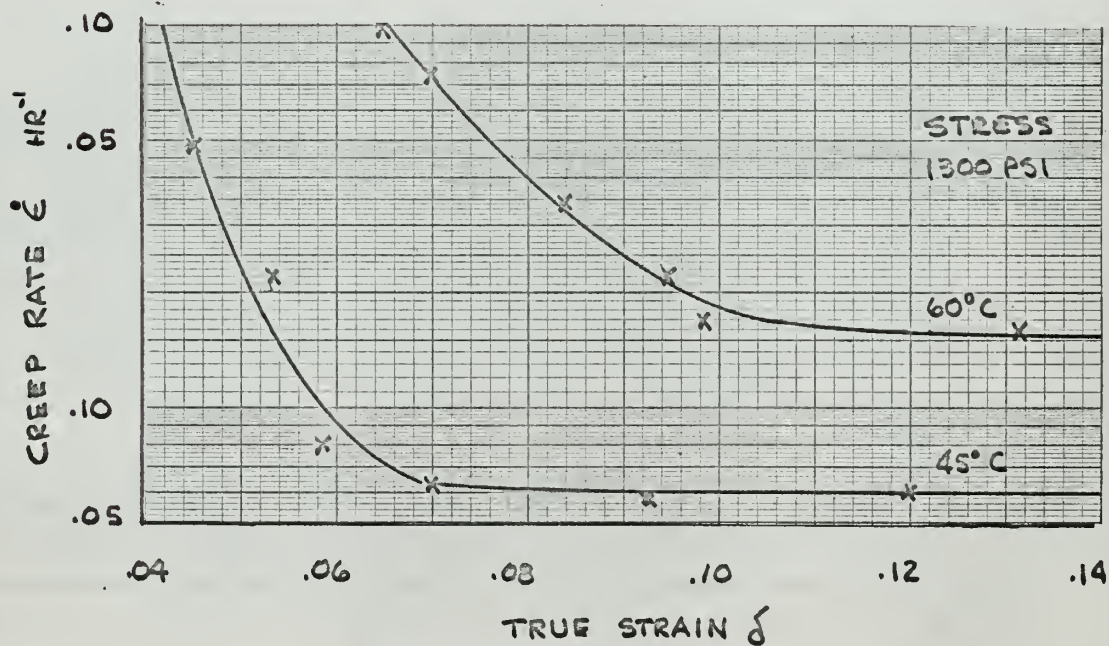
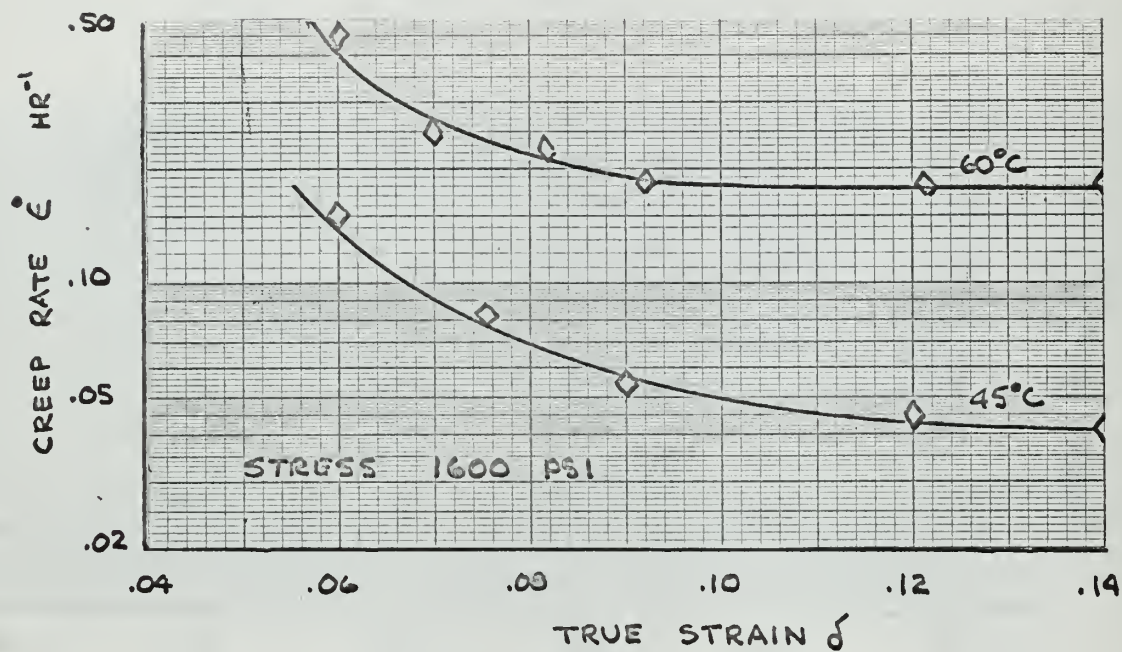
POLYPROPYLENE
 CREEP RATE' VS TRUE STRAIN
 FIGURE 10A



POLYPROPYLENE
 CREEP RATE VS TRUE STRAIN
 FIGURE 10B



POLYETHYLENE
 CREEP RATE VS TRUE STRAIN
 FIGURE II A



POLYETHYLENE
CREEP RATE VS TRUE STRAIN

FIG 11B

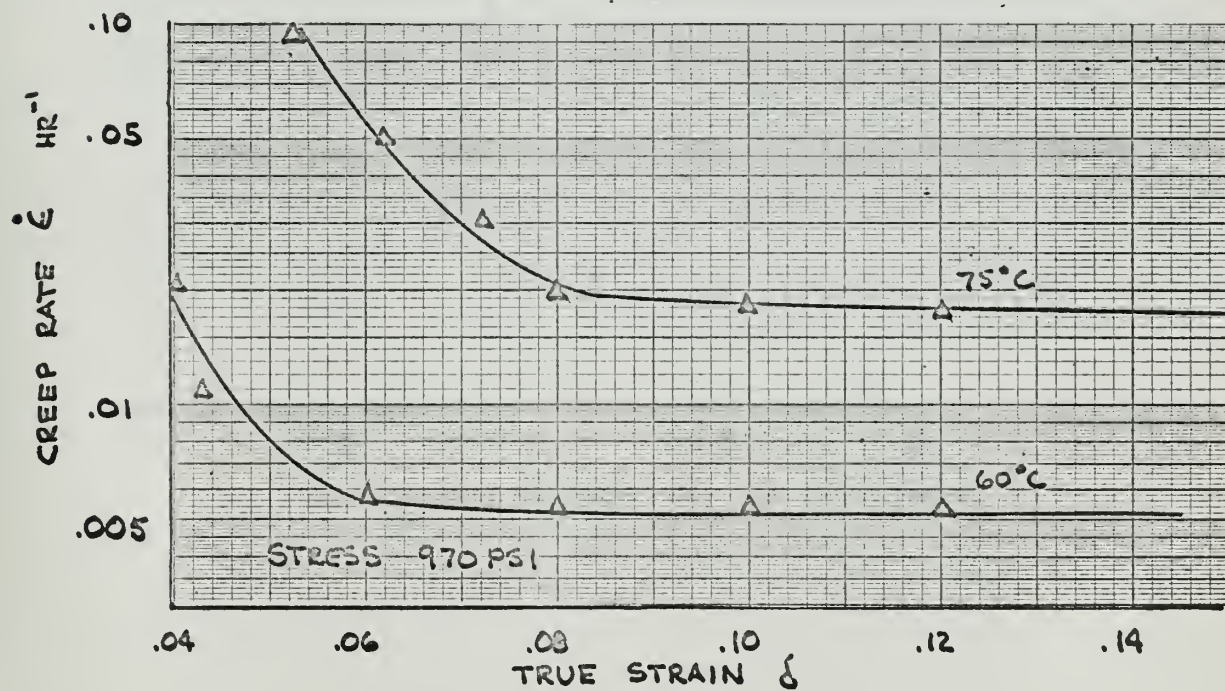
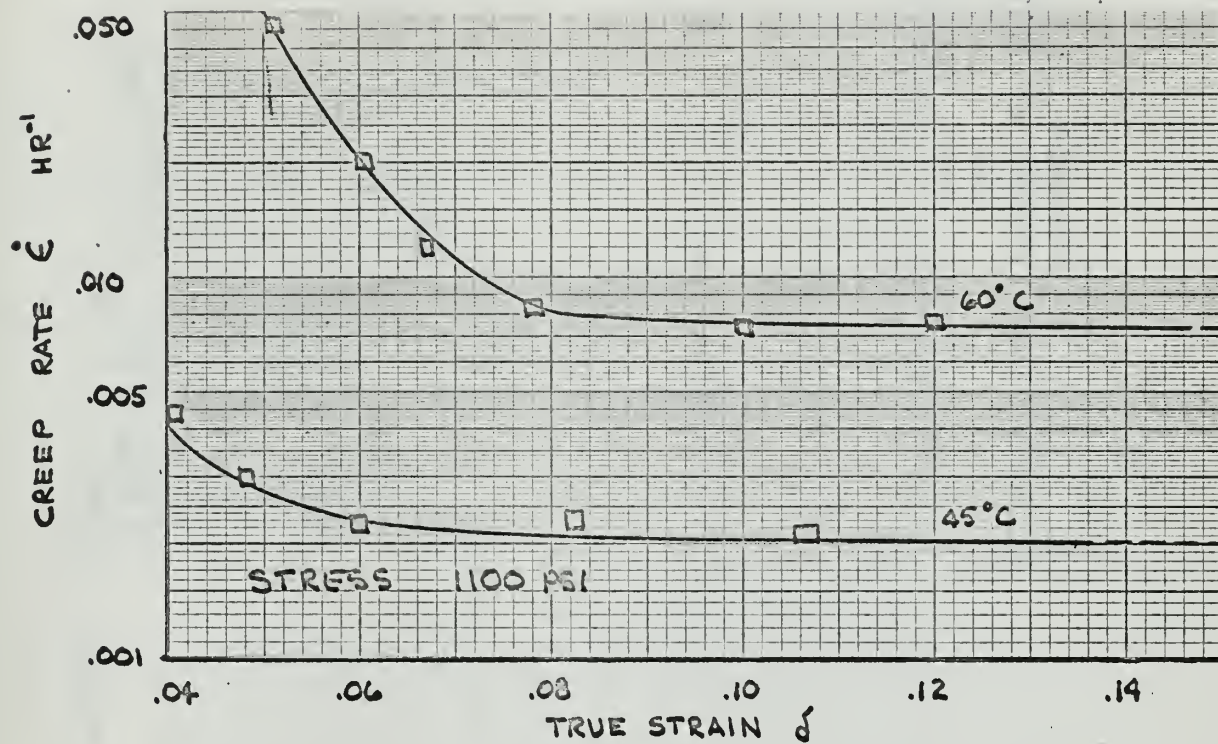
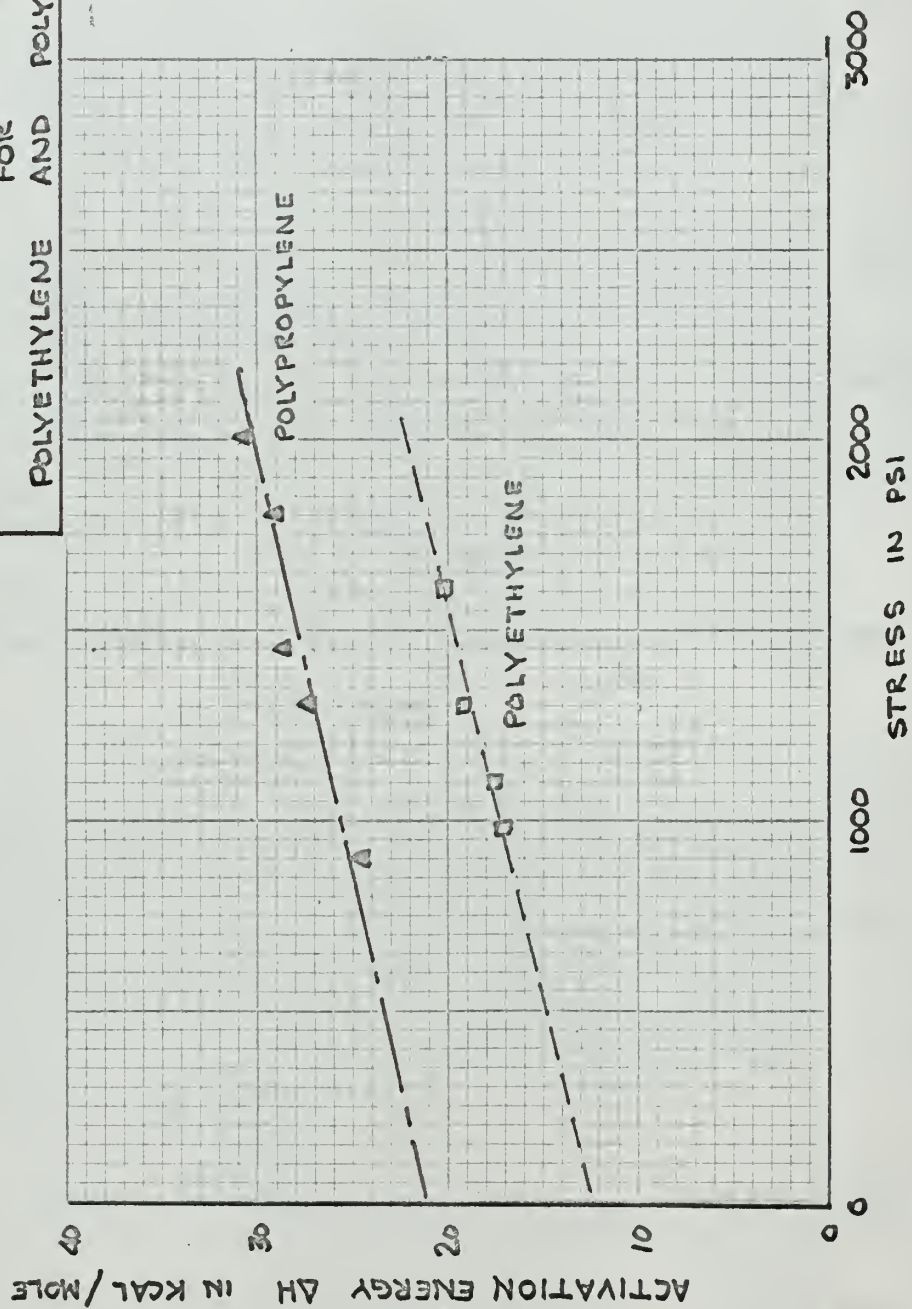


FIGURE 12
ACTIVATION ENERGY VS STRESS LEVEL
FOR
POLYETHYLENE AND POLYPROPYLENE



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14.

KEY WORDS

LINK A

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LINK C

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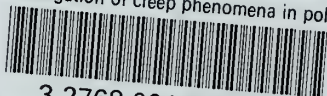




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